Non-collinear spectral coherent combination of ultrashort laser pulses

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Abstract: Non-collinear spectral coherent combining (NCSCC) of ultrashort pulses is analyzed. 2D modeling of the electromagnetic field is performed in case of NCSCC using two or three pulses with different wavelengths. In the case of two pulses, a potentially unwanted spatio-temporal structure of the field appears, corresponding to spatial and temporal modulation of the pulse. By using NCSCC of three 62 fs long pulses with different spectral composition, such spatial-temporal coupling is eliminated and the combined pulse duration in the focal region drops to less than half. The method is scalable to a large number of ultrashort pulses.

OCIS codes: (140.3298) Laser beam combining; (140.7090) Ultrafast lasers; (320.5520) Pulse compression.

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1. Introduction

Quest for the study of matter and vacuum in strong electric and magnetic fields triggered the development of ultrahigh intensity laser systems [1–3]. Limits of the existing laser technology using serial amplification are related to the damage threshold of the optical components. The dimension of the components has to increase in order to accommodate very high energies for the laser pulses. This poses already problems in terms of the technological development for production of large size optical components. One possible path is the parallelization of laser systems. Beam combination represents an effective approach which can improve output power of laser pulses preserving high beam quality. Coherent beam combining technique requires relative phases of the beams to be precisely controlled to a small fraction of the wavelength. This was already successfully demonstrated for continuous wave laser systems [4].

However, there are specific peculiarities of ultraintense pulsed systems that make the coherent combining a challenge, among which the low repetition rates of ultrahigh intensity lasers, the broad bandwidth of such pulses and the condition to avoid transmission optics.

While coherent combination of pulses was reported for laser systems in the MHz range [5,6], it remains a challenge in the 10Hz repetition rate range. The phasing of ultrashort laser pulses requires optical beam path difference control with a spatial resolution corresponding to less than 100 nm. Such spatial accuracy is achievable with interferometric techniques but the temporal resolution of the interferometer measurement shall be better than 0.1ms, in order to be able to follow the acoustic perturbations of the optical paths [7].

The broad bandwidth of the ultrashort pulses requires broadband gain in the system. Ways to generate broadband ultrashort pulses involve the use of nonlinear processes such as optical parametric amplification [8, 9]. Spectral combination of ultrashort pulses using parallel amplifiers with tailored spectral amplification bandwidths makes possible the production of even shorter pulse durations, hence higher peak power. The use of the spectral combination approach and demonstration of pulse reduction was proposed more than 20 years ago [10] and reported in [5, 6, 11–13].

Finally, a major issue posing problems to spectral coherent combination of ultrashort pulses is related to the condition to avoid non-linear optical distortions during the propagation in ma-

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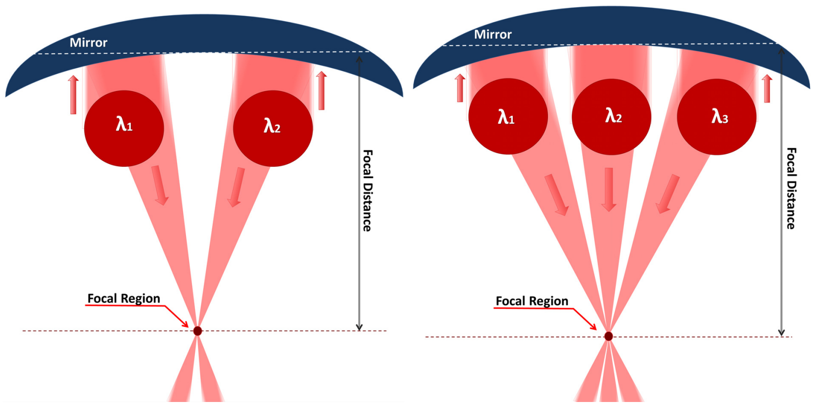

Fig. 1. Schematic design of the optical setup of the laser pulses in the case of spectral beam combining with a) 2 sources, b) 3 sources.

terials, hence to avoid transmission optics. The condition makes the spectral coherent combination difficult as it involves, up to now, the use of transmission elements [14,15] many diffraction gratings [11] or a combination of transmission and difractive optics [16].

A path to avoid the transmission and dispersive optics is identified for the first time in the present work through the analysis of non-collinear spectral coherent combination (NCSCC) of ultrashort pulses. Our proposal is based on only one large mirror, possibly tiled for scalability. It is shown through numerical simulations of the ultrashort pulses propagation that, in the simplest approach involving two ultrashort pulses, the NCSCC introduces specific spatio-temporal interference distortions in the resulting combined pulse. A way to bypass these distortions is identified, based on the use of three or more pulses for NCSCC. The method can be up-scaled to a large number of beams, enhancing in this way the spatio-temporal properties of the resulting combined pulse.

2. Non-collinear spectral coherent combination

We used a commercial software (RSoft, by Synopsys' Optical Solutions Group) that implements the finite difference time domain (FDTD) method for solving Maxwell equations, in order to analyze the electromagnetic field distribution in the common focal region of several laser pulses. The FDTD method can solve difficult problems but it requires large amount of memory and computational time.

The geometry of the problem is illustrated in Fig. 1. The study implies two (fig. 1(a) and three (fig. 1(b) laser sources which propagate initially along the z axis, to the mirror. They have the diameter of 20μm, pulse duration of 62fs and vertical polarization. The 20μm source diameter is specified at a distance of 50μm from the highest point of the parabola, along the propagation axis z, where the field is generated as initial condition. The interval considered for central wavelength values for both cases with two and three laser sources is 0.75-0.854μm with 8nm step. The sources are Gaussian both in space and in time, as follows:

$$\Phi(x,z,t) = Ae^{-x^2/a^2}e^{-t^2/\tau^2}\sin\left(\frac{2\pi}{T}t+\phi_0\right) \tag{1}$$

where A is the field amplitude, a is the source size along the transverse axis x, τ is the pulse duration, T is the period of light and ϕ_0 is the phase, chosen such that the phase is 0 at the maximum of the Gaussian function. For the temporal parameters, units of *ct* are used here further, where c is the speed of light. In this way, 1μm corresponds to 3.33fs.

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The laser beams are emmited in phase. They are focused by the parabolic mirror which has the parent focal distance of 75 μm and the diameter of 160 μm. Taking into account the source diameter of 20μm, the equivalent f-number is 3.75 for one source. The separation of the beams is 40μm from center to center. The contribution to the focal spot is the same for all the Gaussian beams having the same f-number and the same wavelength. Hence, the results of the simulations corresponds, for example, to multiplexing of beams of 20cm focused by parabolic mirror having 75cm focal distance; at 75cm before the focus, the separation of the beams shall be 40cm from center to center.

We studied the electromagnetic field distribution in the focal region from the spatial and temporal point of view. These two aspects are not equivalent, as discussed in [17]. The spatial electromagnetic field analysis is based on the 2D distributions of the electromagnetic field in the focal region, at a given moment in time, when the maximum field is achieved. The temporal evolution envelopes of the electromagnetic field were compared in different points denoted with M in Fig. 2, in the vicinity of the waist of the combined beam at 0.4μm and 0.8μm away from the origin on both sides along x axis.

2.1. Spectral combination of two laser sources

We analyzed the behavior of the resulted EM field distribution in the focal region in three cases: λ_1 = 0.8μm while λ_2 = 0.65μm (Fig. 2(a), λ_1 = λ_2 = 0.8μm (Fig. 2(b), and λ_1 = 0.8μm while λ_2 = 0.838μm (Fig. 2(c).

The spatial extension of the EM pulse in the focal region is represented on the left of the picture 2 at the moment when the composite electric field reaches its maximum. The pulse duration evolution at five points across the focal plane are compared on the right side of Fig. 2 for each of the three cases; the horizontal axis corresponds to time expressed in ct units; Same field input parameters were used, in order to ease the comparison.

One can identify in Figs. 2(a) and 2(c) the beating of the two pulses along the propagation axis z, and interference patterns across the focal region, along the x axis. The two effects build up a tilted EM field structure that might be detrimental for experiments.

Further, it is analyzed the influence of λ_2 variation in a range of 100 nm symmetrically from the central wavelength on the pulse duration and spatial distribution. Figure 3(a) shows the behavior of the pulse duration in case of NCSCC with λ_2 variation in range from 0.75μm to 0.85μm. The temporal FWHM changes, determined for each value of λ_2, correspond to the spectral broadening of the composite EM field in the focus. They are a consequence of the Fourier relation between the spectral composition and the temporal evolution of the pulse.

On the spatial side, the EM field distribution analysis shows the rotation of the central spatio-temporal interference lobe. To characterize this rotation, it is introduced a rotational parameter α (fig. 3(b) as the angle made by the lobe with the propagation direction. Here it can be observed that the value of α parameter increases with the spectral separation of the sources. The tilt increases when the λ_2 values are chosen in such a way to induce the shortening of the pulse duration.

Comparing to the reference case (λ_1 = λ_2=800 nm), there were obtained three times shorter pulses for the cases when λ_2 is equal to 846 nm, proving in this way shorter EM fields from the temporal point of view, as shown in the insets of Fig. 3(a). The drawback is the presence of the tilt in the spatial structure of the composite EM pulse. This asymmetry in the focus can be detrimental to the experiments hence in the next subsection a solution for eliminating it is presented.

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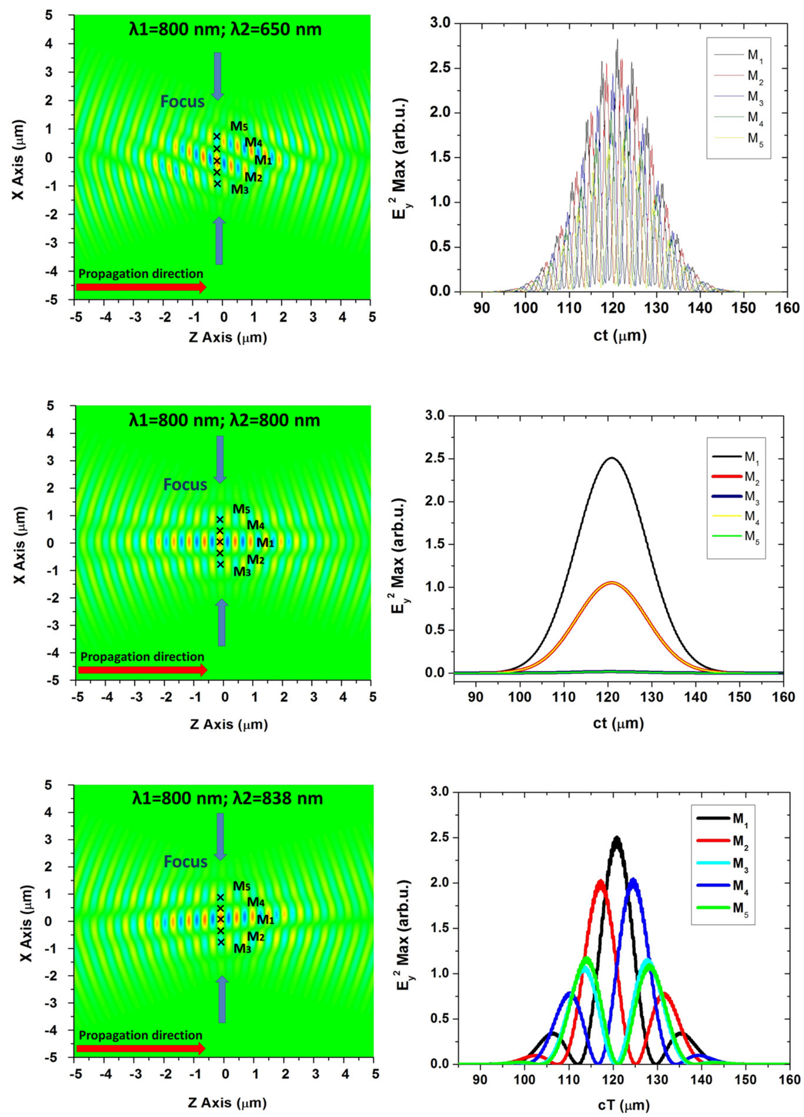

Fig. 2. Spatial and temporal characteristics in the focal region for NCSCC of two laser sources. The 2D plots on the left illustrate the electric field distributions while the right plot shows the temporal evolution of the electric field envelope measured by monitors placed in the points marked with M_i: a) $\lambda_2 = 0.65\mu$m; b) $\lambda_2 = 0.8\mu$m; c) $\lambda_2 = 0.838\mu$m.

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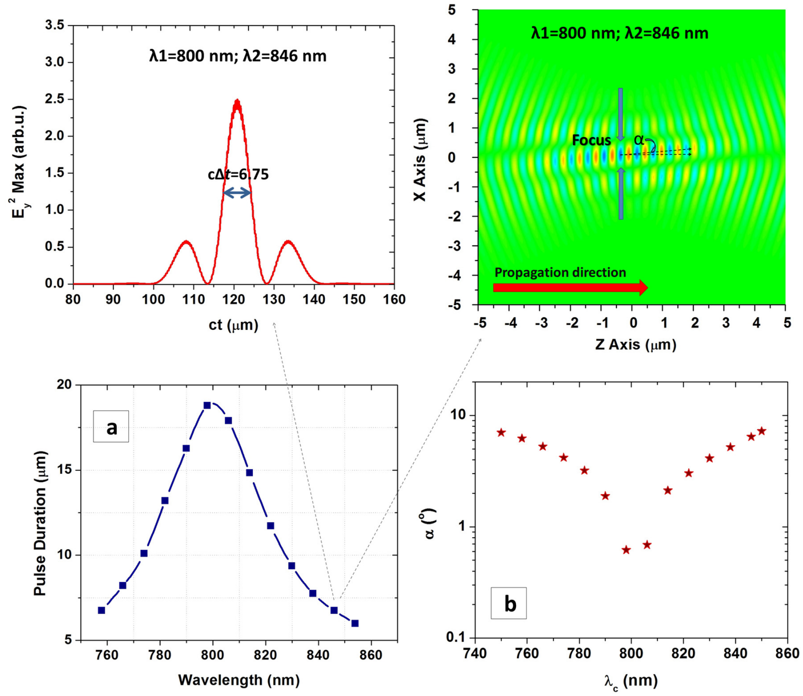

Fig. 3. a) Calculated pulse duration and b) the electromagnetic field distribution rotation in case of wavelength variation (750-850 nm).

2.2. Spectral combination of 3 laser sources

The two sources case discussed above corresponds to a rough analysis of the focus generated by a laser pluse with spatial chirp. The spatial chirp can be estimated as the ratio of the spatial separation and spectral separation of the two sources. The angle of the lobe in the focus corresponds to the spatial chirp of the two pulses.

To annihilate the tilt of the central lobe, a rotation in the opposite direction has to be induced. This can be realized in practice by introducing an additional pulse that generates a spatial chirp with opposite sign in the entrance plane of the system.

The geometry of this approach is depicted in Fig. 1(b). The separation of the beams is 30μm from center to center for two neighboring pulses in the input plane, while the diameter of each source is 20μm. As in the previous case, we varied λ_1 and λ_3 in range from 0.75μm to 0.85μm while λ_2=0.8μm. Figure 4 illustrates the pulse duration evolution under the λ_1 and λ_3 variation conditions. It can be observed the same tendency of decreasing of FWHM value for λ_1 and λ_3 equal to 750 nm and 850 nm respectively as previous case of two laser sources NCSCC.

To investigate the behavior of the EM field distribution of the combined beams in focus in case of λ_1 and λ_3 variation we plotted the 2D distribution of the EM field in focal region for three different value of λ_1 and λ_3 and we determined the corresponding value of FWHM under spatial aspects (Fig. 4). It can be observed that the minimum value of pulse duration corresponds to λ_1= λ_3=750 nm and 850 nm respectively.

Once the third laser source is introduced in the NCSCC configuration, it can be observed that the EM field distribution rotation is compensated due to the wavelength symmetry of the laser sources.

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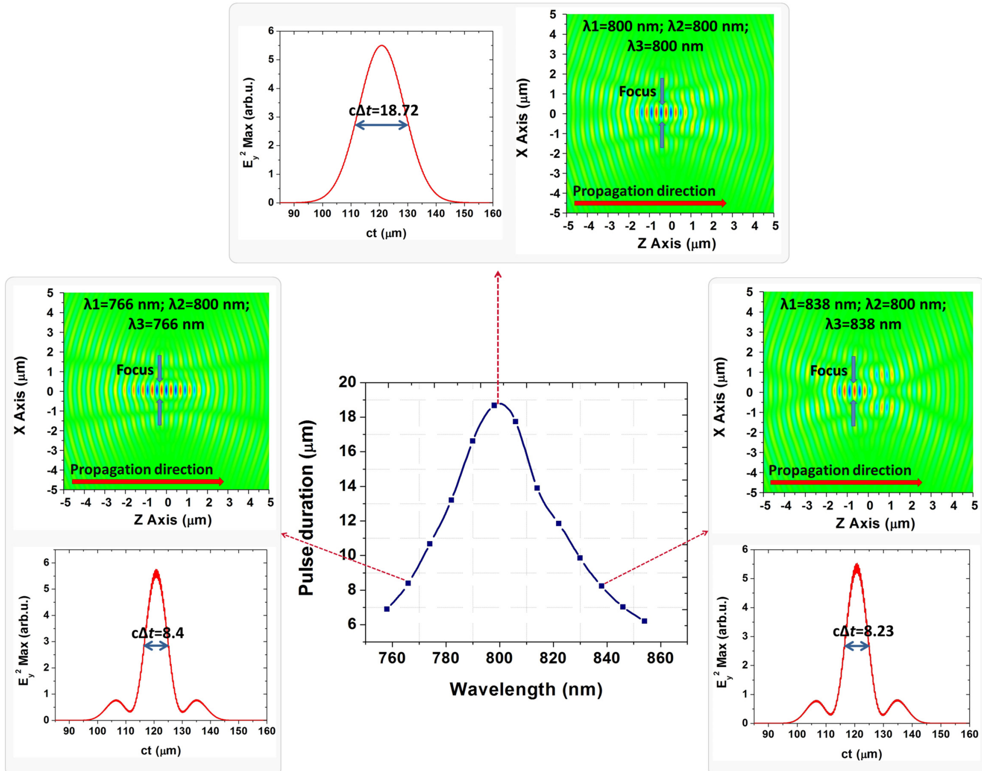

Fig. 4. Calculated pulse duration in case of wavelength variation (750-850 nm) for the case of three laser beams combination.

This approach demonstrates the fact that the temporal modulation of the EM field produces shorter pulses and it is generated by the variation of of λ_1 and λ_3. The spatial interference pattern shows reduced pulse contrast. Further optimization could be performed, depending on the planned experiment.

We can conclude that by combining two or three laser sources and varying the wavelength for one or two of them, we obtain shorter pulses and shorter temporal electromagnetic fields in the form of a temporal modulation.

2.3. *Upscaling the result to a large number of sources*

Of particular interest is the combination of a large number of fiber delivered laser pulses. While the energy delivered through fibers is reaching only the mJ range [18, 19], the repetition rate of fiber lasers can easily reach kHz range and above. International Coherent Amplification Network (ICAN) collaboration [3] is pushing for coherent combination of tens of thousands of fibers in order to produce laser pulses with peak power in the range of 100TW.

One limitation of the method is related to the pulse duration obtainable using identical fiber amplifiers, as their bandwidth is limiting useful pulse duration to few hundreds of fs. However, spectral beam combination was demonstrated to work very effectively in reducing the pulse duration. As fiber amplifiers are now available for wavelength range from one to three micrometer [19], the achievable pulse duration could in principle reach sub-cycle duration. This could boost ICAN capabilities up to the 10PW domain, at kHz repetition rates.

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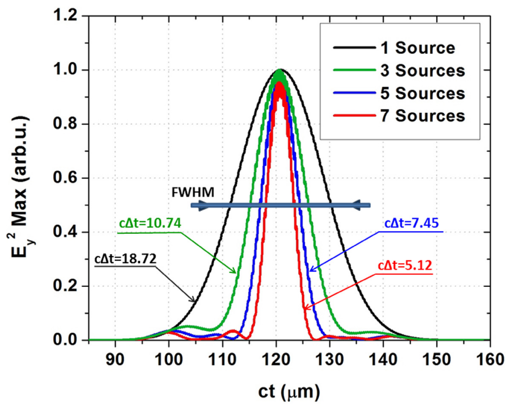

Fig. 5. Calculated pulse duration in case of wavelength variation (750-850 nm) for the case of one, three, five and seven combined laser beams.

It is worth noting that most of the key technologies for NCSCC ICAN were already demonstrated, such as chirped pulse amplification in fiber [18], coherent combination of parallel fiber amplifiers, and subsequent spectral coherent combination of parallel fiber amplifiers with overlaping or non-overlaping spectra [12–14, 20]. However, the problem how to combine such a large number of parallel fiber amplifier outputs in the case of spectral combination had only partial solutions up to now. These approaches proposed up to now are not easily scalable, involve expensive difractive gratings or transmission optics.

The NCSCC method proposed here involves only one reflective mirror to gather all the energy from the parallel fiber amplifiers. For simplicity, the key parameter is the spatial chirp of the distributed input source.

A very rough approximation of linear spatial chirp was illustrated in the case of two sources with different central wavelengths. There, the spatial chirp E could be approximated with the ratio between the spatial separation of the pulses and the spectral separation of the pulses:

$$E = \frac{x_2 - x_1}{\nu_2 - \nu_1} \tag{2}$$

where ν is the frequency corresponding to a given central wavelength λ. In such cases, a tilted pulse is generated with the proposed NCSCC method. The elimination of the tilt is a result of the use of a spatial chirp which is symmetric around the axis x=0. This condition corresponds to a spatial chirp of the input parallel beams with only even high order terms:

$$E(x) = E(-x) \tag{3}$$

The temporal phasing condition of the pulses in the focus has also to be preserved. This corresponds to an absolute optical path difference between all the pulses to be zero in the focus.

Our subsequent simulations with five sources and seven sources provided shorter pulses in smaller spots, as long as the specific symmetry of the spectrum is preserved in respect to the optical axis going through the focus of the mirror. The comparison in the temporal behavior is depicted in Fig. 5. There, the source diameter was 10μm while the distance between two neighbor pulses at input plane was 15μm.

With these spatial and temporal conditions, NCSCC is possible using only one focusing element in reflection. The method is then suitable for the experiments operating at the waist of the combined beam.

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It is important to note that a similar approach, focusing of chirped pulses, is used in multi-photon microscopy under the name of temporal focusing [21]. This is based on the fact that a focused beam with spatial chirp generates enhanced field in the focus. The effect was demonstrated with a digital micromirror device that includes a large number of micromirrors [22]. However, the spatial chirp considered there is only monotonic function of frequency, so the field structure in the focus is not taken into account in detail. The present work indicates how to produce a symmetric field structure, in addition to the temporal focusing effect. This is needed while the microscopic field structure at high intensities strongly influences the processes and results under investigation.

Also, whenever charge and current-free electrodynamic systems are considered, Maxwell equations are homogeneous and, as a consequence, the electromagnetic field evolution at a given point can be obtained as a linear overlap of any free propagating fields compatible with initial and boundary conditions. Hence, the approach used here is valid not only for given wavelength range but for any other spectral region of the electromagnetic field and for an arbitrary number of sources. Gaussian beams are not an exact solution of Maxwell's equations but they are a very close approximation to it [23]. For loose focusing and for multi-cycle pulses, they can be used as a very good approximation of the laser beam. In our simulations we used tightly focused pulses to show that even in such limit case, where numerical solution is better suited than gaussian beam approximation, the effect of symmetric temporal focus is still obtained.

Finally, the simulations are only 2D in space; this configuration is enough in order to induce the reduction of the pulse duration. In order to extend the approach to 3D geometry, one has to consider radial distribution of the sources. This is currently done in continuous wave systems multiplexing where the spatial field distribution corresponding to a large number of sources distributed in plane will generate in the focal plane the corresponding Fourier transformed input distribution.

3. Conclusion

The influence of the wavelength variation on the pulse duration and on the intensity of the field in the focal region was investigated using 2D modeling of the electromagnetic pulse. It is shown that the spectral coherent beam combining technique allows a reduction of the temporal duration of the combined field, reached in the focus. In the case of two pulses, a spatial-temporal structure appears, corresponding to spatial and temporal modulation of the pulse. Using non-collinear spectral coherent beam combination of three pulses in an appropriate way, such spatial-temporal coupling is eliminated and the pulse duration in the focal region is shorter. The main advantage of the method is the use of only one optical component, operating in reflexion, hence avoiding additional nonlinear effects. The method is scalable to a large number of fibers. This study is important for future ultrashort pulse laser experiments at laser facilities employing coherent beam combination such as Extreme Light Infrastructure and ICAN [3].

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